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ENHANCEMENTS OF He^3/He^4 RATIOS FROM INJECTION BY COULOMBIAN RELAXATION

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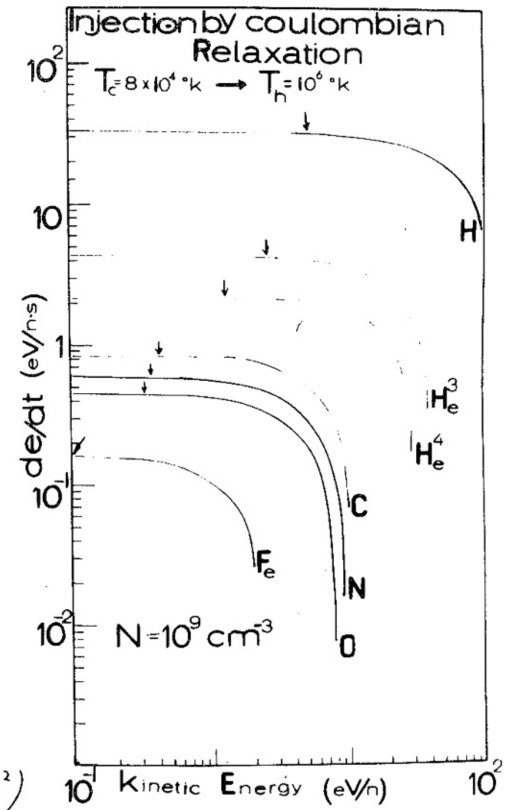
Based in a very simple physical figure it is proposed a new approach to the problem of He^3-rich events that leads in a natural way to a quantitative evaluation of the expected abundances. The enhancements of He^3 over He^4 are determined by Coulombian Relaxation of relatively cold particles into a hotter region.

Introduction

It is shown (Pérez-Peraza and Lara, these proceedings) that alternatively to other possible effects of particle selectivity, prior to the acceleration, during acceleration or during propagation, the effect of Coulombian energy losses during acceleration may also impose different effects of selectivity on the accelerated particles, allowing for a great variety of enhancements or depressions of some nuclear species over others, depending on the physical conditions of the source, such as the degree of ionization, temperature and density. However, Coulombian losses do not allow for depressions of He^4 in relation to He^3, reason why we believe that the observed enhancements in solar particles are generally determined prior to the acceleration process, during an injection stage where particles are relaxed from relatively cold temperatures to higher temperatures. This may occur for instance, when owing to some kind of mass motions a relatively cold material enters into a hotter region where the acceleration process takes place (perhaps by the induced turbulence), or, when particles that were previously accelerated to relatively low energies are trapped in a hot acceleration region, where the thermal energy is higher than the energy of the arriving particles.

Figure 1



Coulombian Relaxation

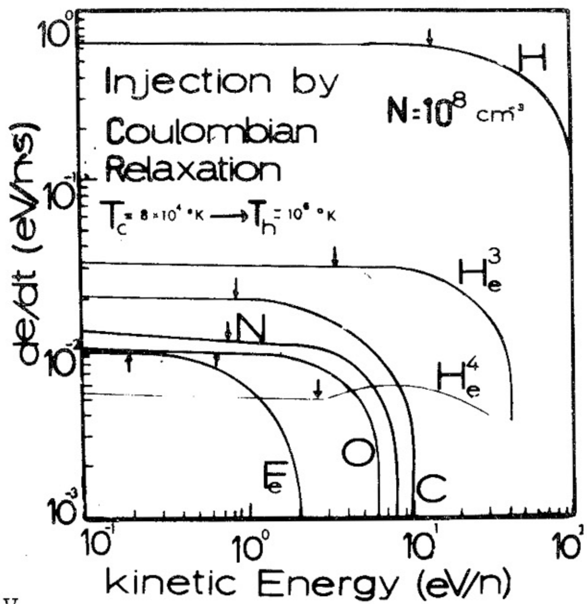
The effect of Coulombian interactions on particles of energy lower than the thermal energy of the target medium, is to heat the particles until they relax to the thermal energy of that medium, whereas at higher energies the effect is the deceleration until thermalization to the local energy. In the former case the rate of Coulombian relaxation has been given by Kihara and Aono (1963), which in the case of a fully ionized medium of Hydrogen may by rewritten as,

$$\left(\frac{dE}{dt}\right)_e = 5.15\cdot10^{-11}\frac{N}{T^{0.5}}\left(\frac{Q}{A}\right)^2\left[0.5\ln\left(T^3/NQ^2\right)+10.31\right]\left(1-3.6\times10^{12}\frac{A}{T}\beta^2\right) \qquad (1) \quad eV/n.s$$

for the contribution of the target electrons, and

$$\left(\frac{dE}{dt}\right)_p = 2.2 \times 10^{-5} \frac{N}{T^{0.5}} \left(\frac{\alpha}{A}\right)^2 \left[0.5 \ln\left(A^2T^3/N(1+A)^2\alpha^2\right) + 10.31\right] \left(1 - 3.6 \times 10^{12} \frac{A}{T} \beta^2\right) eV/n\,s \quad (2)$$

Figure 2



for the contribution of the target protons, where β is the velocity of particles, N the density and T the temperature of the medium where the relaxation takes place. Adding both contributions we obtain for the total relaxation rate, the following expression

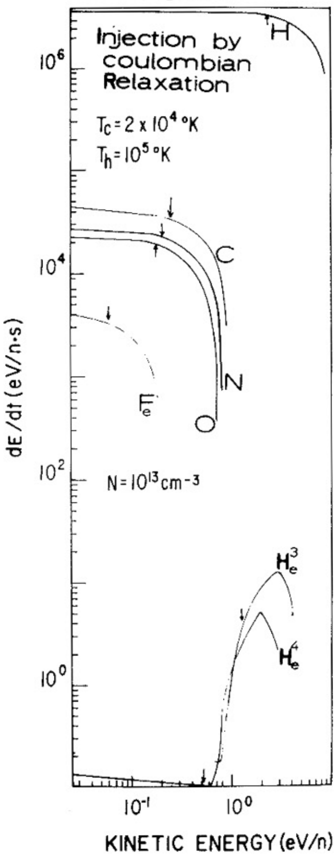
$$\frac{dE}{dt} = \alpha_R \left(1 - 3.6 \times 10^{12} \frac{A}{T} \beta^2\right) eV/n\cdot s \quad (3)$$

where α_R is the relaxation efficiency which depends basically on the charge and mass in the form Q^2/A^2 although it also contains other weaker dependence on the charge and mass. The characteristic time of the relaxation process is given thus as $\tau \sim 1/\alpha_R$. Eq. (3) may be rewritten in terms of kinetic energy as

$$\frac{dE}{dt} = \alpha_R (1 - KE) \qquad eV/n\cdot s \qquad (4)$$

where $K = 7.2 \times 10^{12} A/\mu c^2 T$ with $\mu c^2 = 931.48 \times 10^6$ eV.

Figure 3



Therefore, it can be seen from eqs. (1) to (4) that the He^3 He^3 relaxes faster than He^4 to the thermal energy of the hot region, where presumptively takes place the acceleration process. We have illustrated in Figures 1 to 3 some examples of the relaxation rates, where the arrows indicate the initial energy of particles, and the end of the curves their final energy after relaxation. The most typical sequence of relaxation rates are illustrated in Fig. 1; in the case of very low or very high densities a relaxation rate lower than that of some heavy nuclei is expected as is shown in Fig. 2, or, very low relaxation rates of He^3 and He^4 in a high density medium, as is illustrated in Fig. 3, in which case a high ratio of proton-to-alpha is expected. As we will explain in the next section, the differences in the sequence of the rates for relaxation under different source conditions is mainly due to the effect of the temperature through the local charge states (Table 1), reason why the He^3 and He^4 keep always the same sequence in their relaxation rates. However, as we discussed before in paper SP 1-4, we do not expect in general, a strong effect of particle selectivity on heavy nuclei from this injection stage of Coulombian relaxation, since energy losses during the acceleration process tend to impose severe discriminating effects among them.

The Charge State of Particles

The charges of the concerned ions in eq. (4) have been normalized to the initial local charge states according to the following expression

$$Q = \left[Z - Q_L/(Z - Q_L - Z_{th}^*)\right] Z^* + \left[Z - (Z - Q_L)^2/(Z - Q_L - Z_{th}^*)\right] \quad (5)$$

For $Q_L \leq Q \leq Z$, when Z is the nuclear charge, Q_L are the local charge states that we have displayed in Table 1 for temperatures lower and higher than 1.65×10^4 °K where the neutral and fully ionized hydrogen prevail respectively; $Z^* = Z\,[1-\exp(-129\,\beta/Z^{0.66})]$ is the semi-empirical formula (Barkas, 1963) for the description of the charge behavior according to the velocity of particles (which fits quite correctly the predictions of a Bohr-type theory of charge interchange) and Z^*_{th} is the evaluation of Z^* in the thermal velocity of particles. In this form, particles increase their charge according to their velocity from an initial value Q_L to a value that is limited by the nuclear charge when they reach very high velocities (a very hot region).

TABLE 1

(Q_L), LOCAL CHARGE STATES (Neutral Target Model)

T(°K)	H, H^2, H^3	He^3, He^4	C	N	O	Fe
5.0×10^3	1.0×10^{-7}	1.0×10^{-6}	1.14×10^{-6}	1.0×10^{-8}	1.0×10^{-8}	1.77×10^{-4}
6.3×10^3	1.0×10^{-5}	1.0×10^{-6}	1.99×10^{-4}	3.38×10^{-7}	1.23×10^{-6}	2.37×10^{-2}
8.0×10^3	0.133	1.0×10^{-5}	1.73×10^{-2}	8.5×10^{-5}	3.16×10^{-4}	0.4
1.0×10^4	0.110	1.0×10^{-5}	0.346	7.07×10^{-3}	2.57×10^{-2}	0.676
1.25×10^4	0.486	1.0×10^{-5}	0.891	0.194	0.467	0.958
1.6×10^4	0.649	0.0027	0.977	0.794	0.9	1.038

(Q_L), LOCAL CHARGE STATES (Ionized Hydrogen Target Model)

T(°K)	H, H^2, H^3	He^3, He^4	C	N	O	Fe
2.0×10^4	0.805	0.003	1.0027	0.955	1.0	1.45
4.0×10^4	0.9992	0.7	0.993	1.116	1.116	2.44
8.0×10^4	0.9999	1.2	1.99	1.91	1.9	3.45
1.0×10^5	0.99997	1.96	2.54	2.11	2.09	4.34
1.0×10^6	1.0	2.0	4.7	5.14	6.07	8.12
1.0×10^7	1.0	2.0	5.999	6.99	7.99	16.14
1.0×10^8	1.0	2.0	6.0	7.0	8.0	25

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The Enhancements of He^3 over He^4

Now, let us discuss how this faster rate of Coulombian relaxation of He^3 over He^4 may be translated in enhancements of He^3 over He^4: since autodegradation of turbulence does not allow for an effective acceleration of fast particles (Eischler, 1979) we assume that acceleration initiates from thermal energies, and, as discussed in paper SP 1-4 (Pérez-Peraza and Lara, these proceedings) as far as the light elements are concerned, the acceleration process picks up generally the high energy tails of the particle thermal distribution, such that the enhancement is determined during the lapse of time between the relaxation of both species, since the relaxation time of He^3 is shorter than that of He^4; therefore, if the Coulombian relaxation rate is introduced into an age distribution and converted into energy distribution, the following expression is obtained

$$N(E)dE = \frac{No}{\tau} e^{-t/\tau} dt = \frac{No}{|1-KE_{cold}|} |1-KE|^{-1+1/K} \quad (6)$$

such that by integration up to the energy of particles in the acceleration region, it is obtained the total number of relaxed particles of a given kind

$$J = No \left(1 - \left|\frac{1-KE_{hot}}{1-KE_{cold}}\right|^{1/K}\right) \quad (7)$$

with $E_{hot}=3/2\ (k\ T_{hot})$ and $E_{cold}=3/2\ (k\ T_{cold})$. Therefore we have for the ratio He^3/He^4 in a time t_3 for which the He^3 is already fully relaxed, whereas He^4 is not, the following expression

$$\frac{J_3(He^3)}{J_4(He^4)} = \frac{No_3}{No_4} \left\{ K_4 \left|\frac{1-K_3E_{3\,cold}}{1-K_3E_{3\,hot}}\right|^{\frac{\tau_3}{\tau_4 K_3}} \ln \left|\frac{1-K_4E_4(t_3)}{1-K_4E_{4\,cold}}\right| \right\} \quad (8)$$

where $\tau_3=1/\alpha_3$ and $\tau_4=1/\alpha_4$ are the characteristic times for relaxation of He^3 and He^4 respectively, K_3 and K_4 were defined in eq. (4). $(No_3/No_4)=10^{-4}$ is the ratio of the local abundances of these nuclei in the solar atmosphere and

$$E_4(t_3) = \frac{1}{K_4}\left(1 - \left|\frac{1-K_3E_{3\,hot}}{1-K_3E_{3\,cold}}\right|^{\frac{\tau_3 K_4}{\tau_4 K_3}} \left|1-K_4E_{4\,cold}\right|\right) \quad (9)$$

is the energy reached for the He^4 particles by the time when the He^3 has been completely relaxed. It must be appreciated from eq. (8) that the ratio J_3/J_4 becomes independent of the medium density.

Results and Discussion

As an illustration of this injection process we give here below a random example, according to eq. (8)

T_{cold}(°K)	T_{hot}(°K)	$(J_3/J_4)/(No_3/No_4)$	He^3/He^4
2×10^4	4×10^4	2.3×10^3	0.23
	5×10^4	1.5×10^4	1.5
	6×10^4	1.2×10^5	12

Therefore, we have presented an example of how the ratio He^3/He^4 may be injected into the acceleration process with relative abundances in the order of 0.2 to 10. We feel that although this seems a very simple physical figure, however since active regions in the solar atmosphere show frequent mass motions and high inhomogeneity from the point of view of temperature, this kind of processes may be often associated with the observed enhancements.

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